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ORIGINAL ARTICLE

Simvastatin in the Acute Respiratory Distress Syndrome

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ABSTRACT

BACKGROUND

Studies in animals and in vitro and phase 2 studies in humans suggest that statins may be beneficial in the treatment of the acute respiratory distress syndrome (ARDS). This study tested the hypothesis that treatment with simvastatin would improve clinical outcomes in patients with ARDS.

METHODS

In this multicenter, double-blind clinical trial, we randomly assigned (in a 1:1 ratio) patients with an onset of ARDS within the previous 48 hours to receive enteral simvastatin at a dose of 80 mg or placebo once daily for a maximum of 28 days. The primary outcome was the number of ventilator-free days to day 28. Secondary outcomes included the number of days free of nonpulmonary organ failure to day 28, mortality at 28 days, and safety.

RESULTS

The study recruited 540 patients, with 259 patients assigned to simvastatin and 281 to placebo. The groups were well matched with respect to demographic and baseline physiological variables. There was no significant difference between the study groups in the mean (\pm SD) number of ventilator-free days (12.6 ± 9.9 with simvastatin and 11.5 ± 10.4 with placebo, $P=0.21$) or days free of nonpulmonary organ failure (19.4 ± 11.1 and 17.8 ± 11.7 , respectively; $P=0.11$) or in mortality at 28 days (22.0% and 26.8%, respectively; $P=0.23$). There was no significant difference between the two groups in the incidence of serious adverse events related to the study drug.

CONCLUSIONS

Simvastatin therapy, although safe and associated with minimal adverse effects, did not improve clinical outcomes in patients with ARDS. (Funded by the U.K. National Institute for Health Research Efficacy and Mechanism Evaluation Programme and others; HARP-2 Current Controlled Trials number, ISRCTN88244364.)

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THE ACUTE RESPIRATORY DISTRESS SYNDROME (ARDS) is a common, devastating clinical syndrome characterized by life-threatening respiratory failure requiring mechanical ventilation and by multiple organ failure. In ARDS there is an uncontrolled inflammatory response that results in alveolar damage, with the exudation of protein-rich pulmonary-edema fluid in the alveolar space that results in respiratory failure.¹

The inhibition of 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase with statins has been shown to modify a number of the underlying mechanisms implicated in the development of ARDS.² Statins decrease inflammation and histologic evidence of lung injury in murine models of ARDS.³ Simvastatin reduced pulmonary and systemic inflammatory responses in a human model of ARDS induced by lipopolysaccharide inhalation.⁴ In addition, in a small, single-center, randomized, placebo-controlled study involving patients with acute lung injury, simvastatin ameliorated nonpulmonary organ dysfunction and was safe.⁵ That phase 2 study was not designed or powered to show an effect of simvastatin on clinical outcomes. The aim of this trial was to test the hypothesis that treatment with enteral simvastatin at a dose of 80 mg daily would improve clinical outcomes in patients with ARDS, regardless of the cause.

METHODS

STUDY DESIGN

Patients were adults recruited from general intensive care units (ICUs) in 40 hospitals in the United Kingdom and Ireland (see the Supplementary Appendix, available with the full text of this article at NEJM.org). The study was approved by a national research ethics committee and by the research governance department at each study site in the United Kingdom and by the institutional research ethics committee at each study site in Ireland. The Northern Ireland Clinical Trials Unit coordinated the overall trial, with support from the Health Research Board Galway Clinical Research Facility for centers in Ireland. All the patients or their representatives provided written informed consent. Simvastatin was purchased for use in the study. The funders had no role in the study design, data acquisition, data analysis, or manuscript preparation.

The study design has been published previously,⁶ and the study protocol, including the statistical analysis plan, is available at NEJM.org. The first three authors designed the study, and all the authors made a substantial contribution to the development of the study protocol. The first author wrote the first draft of the manuscript, and all the authors critically reviewed it for important intellectual content. All the authors approved the manuscript and made the decision to submit it for publication. The first and second authors vouch for the integrity, accuracy, and completeness of the data and analyses and for the fidelity of the study to the protocol.

PATIENTS

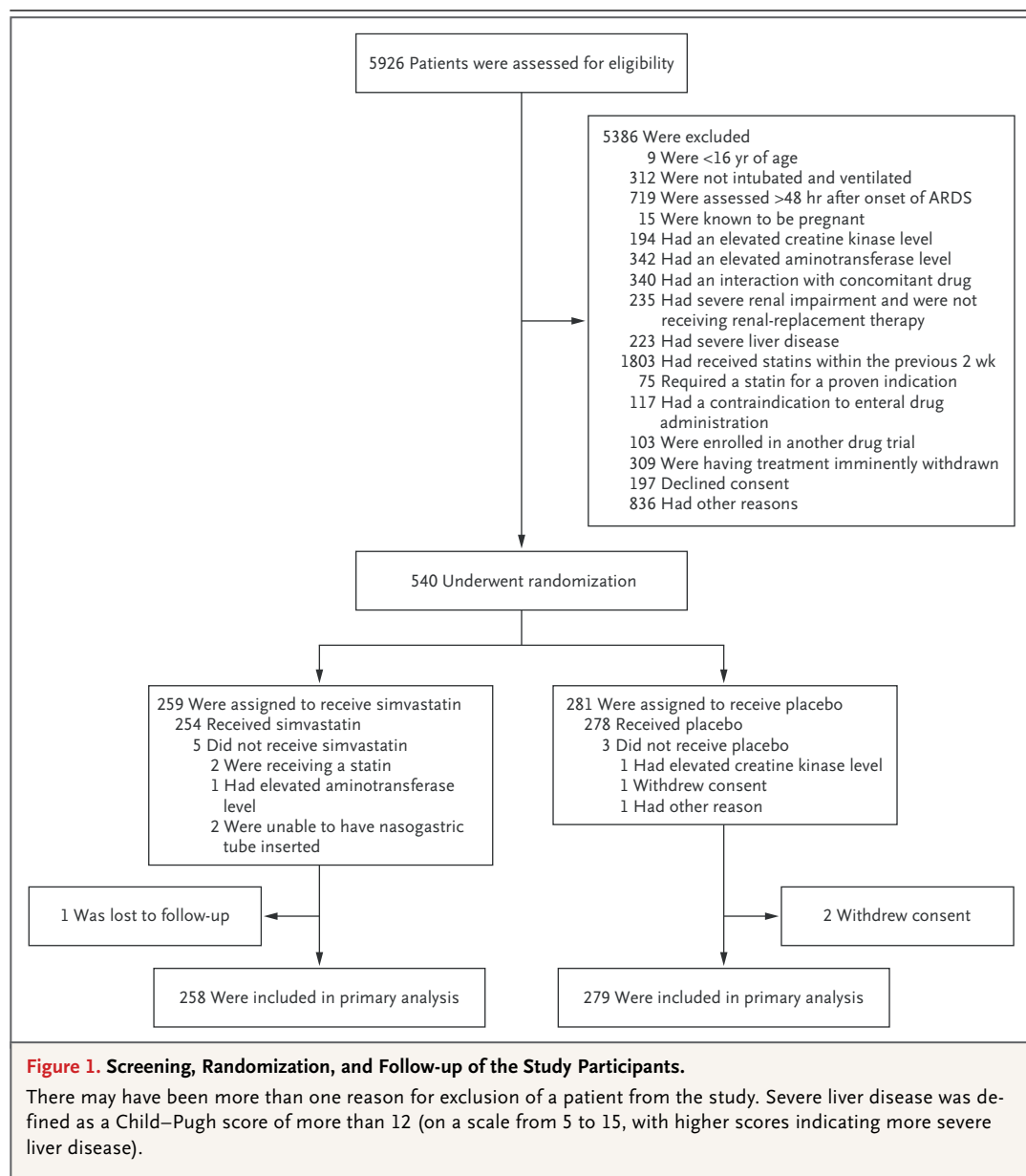
Patients were eligible if they were intubated and mechanically ventilated and were within 48 hours after the onset of ARDS as defined by a ratio of the partial pressure of arterial oxygen (PaO₂) to the fraction of inspired oxygen (FIO₂) of 300 mm Hg or less, if bilateral pulmonary infiltrates consistent with pulmonary edema were present on chest radiography, and if there was no evidence of left atrial hypertension.⁷ The main exclusion criteria are listed in Figure 1, and the full list is provided in the study protocol. The study protocol was amended to permit the enrollment of patients receiving macrolides 9 months into the study and to increase the eligibility criterion regarding the level of alanine aminotransferase or aspartate aminotransferase from more than 5 times the upper limit of the normal range to 8 times the upper limit of the normal range 15 months into the study.

STUDY MEDICATION

Randomization was performed with an automated, centralized, 24-hour randomization service. Patients were randomly assigned to the study groups in a 1:1 ratio with the use of permuted blocks and stratification according to study site and vasopressor requirement (yes vs. no).

Patients received once-daily simvastatin (at a dose of 80 mg) or identical placebo tablets enterally for up to 28 days. The first dose of the study drug was administered as soon as possible, ideally within 4 hours after randomization, and subsequent doses were given each morning starting on the following calendar day.

The study drug was continued until day 28, discharge from critical care (ICU or high-depen-



dency unit, in which patients requiring organ support but not intensive care or invasive mechanical ventilation are treated), death, discontinuation of active medical treatment, development of a clinical condition requiring immediate treatment with a statin, or withdrawal of the patient from the study. The study drug was stopped on safety grounds if the attending clinician determined that this was required, if the level of creatine kinase was more than 10 times the upper limit of the normal range, or if the level of alanine aminotransferase or aspartate aminotransferase

was more than 8 times the upper limit of the normal range.

DATA COLLECTION AND PROCEDURES

At enrollment, each patient's demographic characteristics, ventilatory and physiological variables, and Acute Physiology and Chronic Health Evaluation II (APACHE II) score at the time of admission were recorded. The cause of ARDS was identified by the treating clinician. For each day in the ICU, ventilatory and physiological variables as well as data regarding organ support,

which were based on the Critical Care Minimum Data Set of the United Kingdom,⁸ were recorded. Vital status at 28 days was recorded, but for patients who died, the cause of death was not recorded.

Participating ICUs were encouraged to use low-tidal-volume ventilation at 6 to 8 ml per kilogram of predicted body weight and to maintain a plateau pressure of less than 30 cm of water,⁹ but no specific ventilator-management scheme was promulgated. All other treatment decisions were made by the patients' physicians.

OUTCOME MEASURES

The primary outcome measure was the number of ventilator-free days to day 28, which was defined as the number of days from the time of initiating unassisted breathing to day 28 after randomization.⁶ A detailed definition of ventilator-free days is provided in the study protocol. Secondary outcomes included the change in the oxygenation index and the Sequential Organ Failure Assessment (SOFA) score¹⁰ up to day 28, the number of days free of nonpulmonary organ failure to day 28, death from any cause within 28 days after randomization, death before discharge from critical care or the hospital, and safety. Scores on the SOFA range from 0 to 24, with higher scores indicating more severe disease. The score is calculated from the sum of six individual organ scores (each on a scale from 0 to 4), for the respiratory, cardiovascular, hepatic, coagulation, renal, and neurologic systems. Individual organ scores of less than 2 were used to indicate the absence of clinically significant organ dysfunction.

Additional secondary outcomes are listed in the study protocol. The plasma C-reactive protein level was measured by means of an immunoturbidimetric assay (Randox Testing Services) in blood obtained at baseline and on days 3 and 7.

STATISTICAL ANALYSIS

Sample-size assumptions were based on previously published data.^{5,9} Assuming a mean (\pm SD) number of ventilator-free days of 12.7 ± 10.6 , we estimated that a sample of 524 patients would need to be enrolled in order for the study to have 80% power, at a two-tailed significance level of 0.05, to detect a mean between-group difference of 2.6 ventilator-free days. On the basis of data from the Pulmonary Artery Catheters in Management of Patients in Intensive Care (PAC-Man) trial,

we estimated that the study-withdrawal rate would be 3%,¹¹ and we therefore calculated that the study required a total of 540 patients.

Analyses were performed on an intention-to-treat basis. Because ventilator-free days and days free of nonpulmonary organ failure are known to have a bimodal distribution, the data were initially analyzed by means of Student's t-test, with between-group differences presented as means and 95% confidence intervals. A secondary analysis of these outcome measures involving a bootstrapped t-test was also conducted to support the results of the primary analysis, as detailed in the statistical analysis plan (see the study protocol). For binary outcome measures, risk ratios and associated 95% confidence intervals were calculated. Time-to-event data are presented as Kaplan-Meier plots. The hazard ratios were calculated and the log-rank chi-square test was used to compare survival in the two study groups. All hazard ratios are presented with a two-sided 95% confidence interval. All reported P values are two-sided. Prespecified subgroup analyses were performed to determine whether the treatment effect was modified by age, vasopressor requirement, presence or absence of sepsis, or baseline C-reactive protein level. We used a statistical test of interaction for the subgroup analyses, and the results are reported with 99% confidence intervals.

RESULTS

PARTICIPANTS

Patients were recruited from December 21, 2010, until March 13, 2014. Of the 5926 patients who were assessed for eligibility, 540 (9%) underwent randomization. A total of 8 patients who did not fulfill the eligibility criteria underwent randomization in error, with 4 assigned to each group; these patients were included in the analysis. A total of 5 patients in the simvastatin group and 3 in the placebo group did not receive the assigned study drug. One patient, in the simvastatin group, was lost to follow-up. No data on the primary outcome were available for this patient in the simvastatin group and for 2 patients in the placebo group (Fig. 1).

The baseline characteristics of the patients at randomization were similar in the two study groups, except for a small but significant difference in the $\text{PaO}_2\text{:FIO}_2$ ratio, which was lower in the simvastatin group than in the placebo group

(Table 1). The main causes of ARDS were pneumonia and sepsis. At day 3, the tidal volume in the simvastatin group did not differ significantly from that in the placebo group; the mean difference was 0.05 ml per kilogram of predicted body weight [95% confidence interval (CI), -0.61 to 0.71; $P=0.89$].

Patients received the study drug for a mean of 10.2 ± 7.1 days in the simvastatin group and 11.0 ± 7.9 days in the placebo group ($P=0.23$). The most common reasons for discontinuation of the study drug were discharge from critical care, death, and an adverse event that was considered to be related to the study drug. A total of 5 patients assigned to simvastatin and 3 assigned to placebo received treatment with nontrial statins (Table S1 in the Supplementary Appendix).

OUTCOMES

The number of ventilator-free days did not differ significantly between the two study groups (12.6 ± 9.9 days with simvastatin and 11.5 ± 10.4 days with placebo; mean difference, 1.1 days [95% CI, -0.6 to 2.8]; $P=0.21$). There was also no significant between-group difference in the number of ventilator-free days after adjustment for the baseline $\text{PaO}_2\text{:FIO}_2$ ratio (mean difference, 1.4 days [95% CI, -0.3 to 3.2]; $P=0.10$).

The change from baseline to day 28 in the oxygenation index did not differ significantly between the two groups (Tables S2 and S3 in the Supplementary Appendix), nor did the SOFA score (Table S2 in the Supplementary Appendix). There were no significant differences in the number of days free of nonpulmonary organ failure or in mortality at 28 days. Mortality at ICU discharge or hospital discharge was also not significantly different between the two groups (Table 2). Among survivors, the mean duration of the ICU stay was 13.9 ± 14.4 days in the simvastatin group and 14.4 ± 13.3 days in the placebo group (mean difference, -0.5 days [95% CI, -3.2 to 2.2]; $P=0.71$); the mean duration of the hospital stay was 37.7 ± 64.5 days and 35.4 ± 31.1 days, respectively (mean difference, 2.3 days [95% CI, -8.0 to 12.6]; $P=0.66$). From randomization to day 28, there were no significant differences between the two groups in the probability of breathing without assistance or the probability of survival (Fig. 2).

Subgroup analyses did not suggest that the effects of simvastatin were modified by any of the

Table 1. Characteristics of the Patients at Baseline.*

Characteristic	Simvastatin (N=259)	Placebo (N=280)
Age — yr	53.2 \pm 16.1	54.4 \pm 16.7
Male sex — no. (%)	137 (52.9)	170 (60.7)
Sepsis — no. (%)	189 (73.0)	218 (77.9)
Cause of ARDS — no. (%)†		
Smoke or toxin inhalation	1 (0.4)	2 (0.7)
Gastric-content aspiration	21 (8.1)	29 (10.4)
Thoracic trauma	22 (8.5)	10 (3.6)
Pneumonia	161 (62.2)	154 (55.0)
Sepsis	106 (40.9)	118 (42.1)
Pancreatitis	5 (1.9)	17 (6.1)
Nonthoracic trauma	4 (1.5)	8 (2.9)
Other	30 (11.6)	36 (12.9)
APACHE II score‡	19.4 \pm 6.9	18.3 \pm 6.2
SOFA score§	8.5 \pm 3.2	8.8 \pm 2.9
Vasopressor-dependent — no. (%)	169 (65.3)	187 (66.8)
Lowest mean arterial pressure — mm Hg	65.4 \pm 9.3	64.9 \pm 8.4
Inspiratory plateau pressure — cm of water	23.6 \pm 6.07	23.6 \pm 6.03
Tidal volume — ml/kg of predicted body weight¶	8.1 \pm 2.8	8.1 \pm 2.6
$\text{PaO}_2\text{:FIO}_2$ — mm Hg	123.0 \pm 54.8	132.4 \pm 55.4
Oxygenation index — cm of water/mm Hg	15.0 \pm 11.6	14.9 \pm 11.9
Alanine aminotransferase — U/liter	45.5 \pm 47.1	45.8 \pm 43.2
Aspartate aminotransferase — U/liter	59.9 \pm 49.4	65.3 \pm 63.9
Creatine kinase — U/liter	327.2 \pm 499.3	298.3 \pm 487.7

* Plus-minus values are means \pm SD. There were no significant differences in baseline characteristics between the study groups except for the ratio of partial pressure of arterial oxygen (PaO_2) to the fraction of inspired oxygen (FIO_2) ($P=0.049$). For one patient who had been randomly assigned to the placebo group, baseline data were not available because consent was withdrawn, including permission to use the data collected to the point of study withdrawal. †ARDS denotes acute respiratory distress syndrome.

‡ Patients may have had more than one cause of ARDS identified.

§ Scores on the Acute Physiology and Chronic Health Evaluation (APACHE) II scale range from 0 to 71, with higher scores indicating more severe disease.

¶ Scores on the Sequential Organ Failure Assessment (SOFA) scale range from 0 to 24, with higher scores indicating more severe disease.¹⁰

¶ The predicted body weight was calculated as 2.3 kg for each inch of height above 60 in. (152 cm) added to a base weight of 50.0 kg for men or 45.5 kg for women.

variables investigated. There was no significant interaction between treatment and age ($P=0.62$), vasopressor requirement ($P=0.17$), presence or absence of sepsis ($P=0.50$), or baseline C-reactive protein level ($P=0.77$) (Table S4 in the Supplementary Appendix).

Table 2. Main Clinical Outcomes.*

Variable	Simvastatin	Placebo	Student's t-Test		Bootstrapped t-Test	
			Difference or Risk Ratio (95% CI)	P Value	Difference (95% CI)	P Value
Ventilator-free days, randomization to day 28†						
No. of patients in analysis	258	279				
No. of days (95% CI)	12.6±9.9 (11.3 to 13.8)	11.5±10.4 (10.2 to 12.7)	1.1 (−0.6 to 2.8)‡	0.21	1.1 (−0.7 to 2.8)	0.22
Days free of nonpulmonary organ failure, randomization to day 28§						
No. of patients in analysis	257	279				
No. of days (95% CI)	19.4±11.1 (18.0 to 20.8)	17.8±11.7 (16.4 to 19.2)	1.6 (−0.4 to 3.5)‡	0.11	1.6 (−0.3 to 3.5)	0.10
Death from any cause						
No. of patients in analysis	259	280				
Randomization to day 28 — no. (% [95% CI])	57 (22.0 [17.0 to 27.1])	75 (26.8 [(21.6 to 32.0)])	0.8 (0.6 to 1.1)¶	0.23	—	—
Before discharge from critical care — no. (% [95% CI])	56 (21.6 [16.6 to 26.6])	70 (25.0 [19.9 to 30.0])	0.9 (0.6 to 1.2)¶	0.36	—	—
Before discharge from hospital — no. (% [95% CI])	67 (25.9 [20.5 to 31.2])	90 (32.1 [26.7 to 37.6])	0.8 (0.6 to 1.1)¶	0.13	—	—

* Plus-minus values are means ±SD.

† Ventilator-free days were defined as the number of days from the time of initiating unassisted breathing to day 28 after randomization (see the study protocol). Patients who died before day 28 were assigned 0 ventilator-free days.

‡ The data show the difference in the number of days.

§ The definition of days free of nonpulmonary organ failure is provided in the study protocol. Patients who died before day 28 were assigned 0 days free of nonpulmonary organ failure. Organs were considered to be failure-free after patients were discharged from the intensive care unit (ICU).

¶ The data show the risk ratio.

|| Critical care was defined as care in the ICU or the high-dependency unit, in which patients requiring organ support but not intensive care or invasive mechanical ventilation are treated.

There were no significant differences between the simvastatin and placebo groups in the plasma C-reactive protein level at baseline, at day 3, or at day 7 (Table S6 in the Supplementary Appendix). There was also no significant between-group difference in the change in the C-reactive protein level from baseline to day 7 (Table S5 in the Supplementary Appendix).

SAFETY

Overall, adverse events related to the study drug were significantly more common in the simvastatin group than in the placebo group. The majority of the adverse events were related to elevated creatine kinase and hepatic aminotransferase levels. The numbers of serious adverse events

(other than those reported as trial outcomes, such as death) were similar in the two groups (Table S7 in the Supplementary Appendix). There was no significant between-group difference in the proportion of patients with nonpulmonary organ dysfunction, as measured by a SOFA score of less than 2 for each organ (Table S8 in the Supplementary Appendix).

DISCUSSION

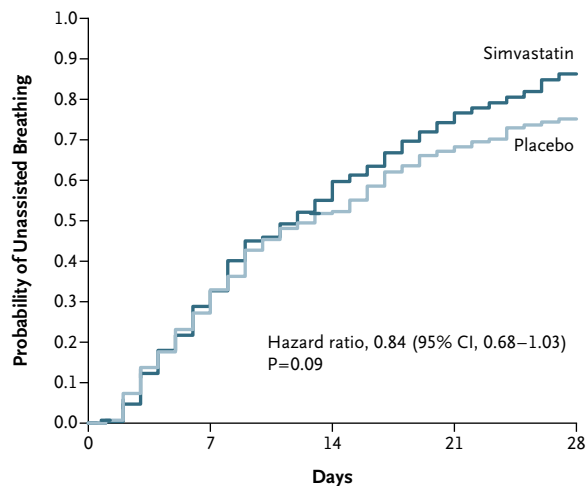
In this large, multicenter, double-blind, randomized, placebo-controlled clinical trial involving patients with ARDS, simvastatin, as compared with placebo, did not improve clinical outcomes. Simvastatin was associated with an increase in

adverse events; however, there was no increase in serious adverse events. The recent Statins for Acutely Injured Lungs from Sepsis (SAILS) study, which involved patients with sepsis-associated ARDS, showed that rosuvastatin did not improve clinical outcomes, as compared with placebo, and was associated with fewer days free of renal and hepatic failure.¹² The population in our study was not limited to patients with sepsis-associated ARDS, and therefore, taken together, these data show little value in the routine use of statins in ARDS, regardless of the cause.

We used simvastatin at a dose of 80 mg on the basis of our previous data from clinical studies,^{4,5} in which simvastatin improved surrogate outcomes and biologic mechanisms implicated in ARDS. The data from our current study and the SAILS trial show that neither a lipophilic statin (simvastatin) nor a hydrophilic statin (rosuvastatin) is effective in the treatment of ARDS. The high dose of simvastatin (80 mg) used in this trial was selected on the basis of our pilot data⁵ as well as preclinical data³ and observational studies.^{13,14} Although we did not measure simvastatin concentrations, it is likely that an adequate simvastatin concentration was achieved, for several reasons. A prior study involving critically ill patients showed that simvastatin at a daily dose of 80 mg produced systemic drug concentrations that were in the high therapeutic range.¹⁵ Furthermore, patients received simvastatin for a mean of 10 days. Finally, the increased incidence of expected statin-related adverse events suggests that sufficient simvastatin concentrations were achieved. The lack of an effect on the plasma C-reactive protein level suggests that statins cannot modulate inflammation sufficiently to provide a beneficial clinical effect in ARDS. It is possible that HMG-CoA reductase is already substantially inhibited, as reflected by the low cholesterol levels seen in critically ill patients.¹⁶

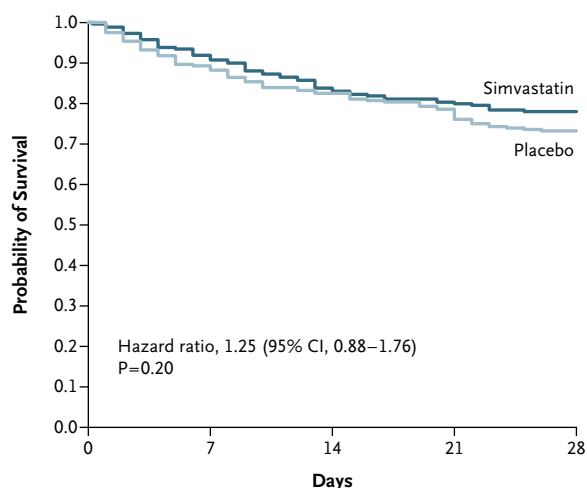
Although the incidence of treatment-related adverse events was higher in the simvastatin group than in the placebo group, the number of serious adverse events was similar in the two groups. The finding that the proportion of patients with no organ dysfunction, as measured by the SOFA score, was similar in the two groups over the course of the study is reassuring. The absence of serious harm with simvastatin in this

A Unassisted Breathing



No. at Risk					
Simvastatin	258	166	87	43	19
Placebo	279	178	102	60	33

B Survival



No. at Risk					
Simvastatin	259	238	217	208	202
Placebo	280	250	231	220	205

Figure 2. Probabilities of Survival and Breathing without Assistance from Randomization to Day 28, According to Whether Patients Received Simvastatin or Placebo.

Data regarding the primary outcome of unassisted breathing to day 28 were available for 258 patients in the simvastatin group and for 279 in the placebo group (Panel A). Data regarding survival at 28 days were available for 1 additional patient in each study group (Panel B): in the simvastatin group, we were able to determine survival status for 1 patient although we did not have primary-outcome data; and in the placebo group, 1 patient who withdrew from the study allowed the use of limited additional data including survival to be collected and used.

population provides reassurance with regard to the safety of statins being used for other proven indications in patients with ARDS.

We recruited a heterogeneous cohort of patients with ARDS due to any cause to ensure that our findings would be generalizable. Recent data have suggested that it may be possible to identify specific phenotypes within ARDS.¹⁷ Future studies may identify a subpopulation of patients with ARDS who might have a greater response to simvastatin than was observed in our study.

Although we recommended best practice for the treatment of ARDS, including lung-protective ventilation, we did not record, in detail, all the aspects of clinical management. At randomization, the mean tidal volume was 8.1 ml per kilogram of predicted body weight, and it is possible that this level of tidal volume confounded the potential effects of simvastatin. However, this situation is unlikely, given the similar absence of benefit with rosuvastatin in the SAILS study, in which the mean tidal volumes were 6.6 and 6.8 ml per kilogram of predicted body weight in the two study groups.¹² Our data on tidal volume and plateau pressure are consistent with those observed in other clinical trials in critical care in which ventilation was not strictly defined in the protocol.¹⁸

Despite promising findings in early-phase clinical trials of statins for the treatment of ARDS, these findings have not been translated into improvements in patient-centered outcomes in large clinical trials. A recent randomized, controlled trial involving patients with ventilator-associated pneumonia showed that simvastatin did not improve clinical outcomes.¹⁹ Data on efficacy that are based on surrogate outcomes must be considered with caution, given the absence of a clear correlation between surrogate and patient-centered outcomes. Surrogate outcomes that more closely track patient outcomes need to be identified.

In conclusion, our study showed that simva-

statin, as compared with placebo, did not increase the number of ventilator-free days or improve other clinical outcomes in patients with ARDS, although it had an acceptable safety profile. These results do not support the use of simvastatin in the management of ARDS.

The views expressed in this article are those of the authors and not necessarily those of the Medical Research Council (MRC), National Health Service, National Institute for Health Research (NIHR), or Department of Health.

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Dr. McAuley reports receiving fees from GlaxoSmithKline for serving on advisory boards, consulting fees from GlaxoSmithKline and Peptinnovate, and clinical-trial support from GlaxoSmithKline paid to his institution; he is also a named inventor on a pending, unlicensed patent for the use of a pharmacotherapy (not a statin) for the treatment of the acute respiratory distress syndrome. Dr. O'Kane reports receiving clinical trial support from GlaxoSmithKline paid to her institution and travel support from AstraZeneca. Dr. Perkins reports receiving fees from GlaxoSmithKline for consulting and for serving on advisory boards. No other potential conflict of interest relevant to this article was reported.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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